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CONTROL OF THE DYNAMICS OF A TWO-PHASE LIQUID-GAS WEIGHTLESS MEDIUM WITH THE AID OF SURFACE EFFECTS

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CONTROL OF THE DYNAMICS OF A TWO-PHASE LIQUID-GAS WEIGHTLESS MEDIUM WITH THE AID OF SURFACE EFFECTS

V. N. Serebryakov

The necessity of developing special methods for organizing hydrodynamic processes in two phase (gas-liquid) systems in the absence of gravity is considered.

The necessary conditions and the possibility of satisfying them through the rational utilization of surface energy are considered. It is shown that it is possible to stabilize the surface of the boundary between the gas and the liquid in a perturbed two-phase medium and to stabilize the volumetric separation of the phases by means of hydrophobic and hydrophilic rigid frames (screens). The conditions which provide for the optimum characteristics of the screens are determined.

A theoretical investigation is conducted on the dynamics of elements associated with the perturbed two-phase medium when it interacts with screens of various types. The numerical solutions of the boundary value problems describing the behavior of liquid drops and gas bubbles were obtained with the aid of the M-20 electronic digital computer and indicate that it is possible to achieve a process of phase separation in the considered system. The results of experimental investigations which confirm the conclusions are presented.

The general sphere of problems associated with the effect of weightlessness on the mechanics of the two-phase system (gas-liquid) can be divided into two basic domains if certain assumptions are made: /713*

- The domain of the hydrostatics of weightlessness, which includes problems of form equilibrium and stability of the surface separating the gas and the liquid (the Bond characteristic criterion-$Bo \ll 1$),

- The domain of hydrodynamics, which includes the problems of organization of such processes as boiling, condensation, bubbling, electrolysis, etc., under conditions of weightlessness. These are closely associated with the problem of phase separation in a perturbed gas-liquid medium (the Weber characteristic criterion-$We > 1$).

Theoretical and experimental investigations in the field of hydrostatics make it possible, at this time, to establish basic directions and methods of solving hydrostatic problems, including the problems of controlling the parameters of the surface separation.

The processes pertaining to the second group (which are usually called

*Numbers given in margin indicate pagination in original foreign text.

hydrodynamic processes) are usually characterized by the presence of intense internal perturbations and the relative prevalence of inertial forces (We>1) which in the general case are nonstationary in magnitude and direction. In this connection the conditions for the formation of a stable boundary separating the phase and con itons for the normal flow of the above processes are absent under conditions of weightlessness. The organization of such processes requires the development of special methods for controlling the dynamics of the perturbed two-phase medium under conditions of weightlessness.

We note the following characteristic features associated with the mechanics of a perturbed two-phase medium in a gravitational field:

- the presence of a dynamically stable (equipotential) free surface,

- the existence of a hydrostatic mechanism which provides for a separation of phases on the free surface and for the organized motion of inclusions (drops, bubbles), distributed over the volume, toward the surface. /714

Assuming that it is sufficient to have these conditions satisfied, we shall show that when gravity is absent each of them may be realized by the rational utilization of the energy associated with surface interactions in the system.

1. By using the well-known mechanism of surface interactions we shall show that the boundary separating the phases in a perturbed medium may be stabilized by at least two methods depending on the adhesion to the solid body:

- on the surface of the hydrophilic frame (fig.1a),

- on the surface of the hydrophobic (fig.1b) rigid frame (in the future it will be referred to as the screen).

If the perturbations in the medium are reduced to the fluctuations of pressure P, which act on the separation surface, then obviously the latter will be stably suspended on the exterior surface of the frame (facing the nonwetting phase) when we have the condition

$$0<\frac{P}{P_\sigma}<1, \tag{1}$$

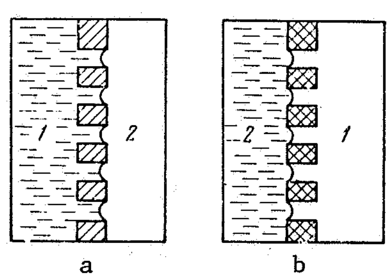

Figure 1. Schematic showing the stabilization of the boundary separating the phase : a-hydrophilic frame, b-hydrophobic frame, 1-wetting phase, 2-nonwetting phase.

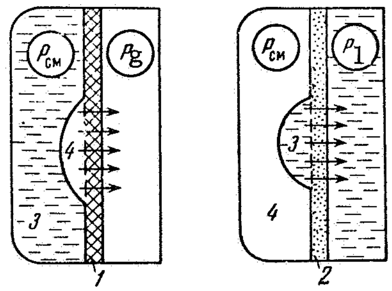

Figure 2. Schematic showing the semi-permeabilities: 1- hydrophobic screen, 2-hydrophilic screen, 3-liquid, 4-gas, P_{cm}-pressure in the gas-liquid medium, P_g-gas pressure, P_p-pressure of the liquid.

where $P\sigma=2\sigma|\cos\theta|/r$ is the surface pressure, σ is the surface tension at the boundary separating the gas and the liquid and θ is the contact angle on the screen material.

This condition can be satisfied always by selecting the dimension r of the screen mesh in a corresponding manner.

2. The separation surfaces fixed in this manner will have the general properties of selective permeability (the first with respect to the liquid and the second with respect to the gas; see figure 2):

- when the inclusion comes in contact with the surface of the wetted screen it will pass through the structure due to the pressure discontinuity on the surface of the boundary produced by the local curvature in the mesh.
- The regions which are in contact with the nonwetted phase will be "blocked" (when condition (1) is satisfied), i.e., the condition of phase separation on the free surface will be satisfied.

The maximum permissible velocities (from condition (1)) for the flow of phases over the structure may be determined by means of relationships from the theory of filtration (ref. 1) /715

$$u_{\max}=\frac{1}{4c}\frac{\sigma}{\mu}|\cos\theta|\frac{W}{s}r, \tag{2}$$

where μ is the dynamic viscosity of the phase, W is the relative content of cavities in the structure, c is the anisotropy coefficient of the structure, s is the screen thickness.

We can see from (2) that the maximum overflow velocity is determined by the viscous-capillary characteristics of the phase, by the wetting conditions, and depends in a linear manner on the dimensions of the mesh. In this connection it is of interest to consider the problem of selecting the dimensions of the mesh which would provide for an optimum relationship between the stability of the fixed separation surface and the carrying capacity of the screen.

Designating by P_{Φ} the pressure loss produced by overflow, we introduce the quantity $\Delta P_y = P\sigma - P_\Phi$ which characterizes the "stability reserve" for the separation surface. Assuming laminar conditions we obtain

$$\Delta P_y = \frac{k_1}{r} - u_\Phi \frac{k_2}{r^2}, \qquad (3)$$

where $k_1 = 2\sigma|\cos\theta|$, $k_2 = 8\cos\mu/W$, u_Φ is the velocity of phase overflow along the structure.

Figure 3 represents the functions $P_\sigma(r)$ and $P_\Phi(r)$ during constant velocity for the case of the water-air medium. The zone of selective permeability lies under the curve P_σ in the diagrams. The nature of the curves indicates that there is a maximum value of ΔP_y when the dimension of the mesh has a definite value r^*. From the condition of a maximum (3) $(\Delta P_y)'_r = 0$ we obtain the optimum dimension of the mesh

$$r^* = 2\frac{k_2}{k_1} u_\Phi,$$

which provides, for a given velocity u_Φ, a maximum "stability reserve" /716

$$(\Delta P_y)_{max} = \frac{k_1^2}{4k_2}\frac{1}{u_\Phi},$$

or for a given "stability reserve" it provides the best screen carrying capacity of $u_{\Phi\ max} = (k_1^2/4k_2)\ (1/\Delta P_y)$.

3. Let us investigate the interaction of the two-phase medium with the considered screens. In particular the investigation will be carried out for a system consisting of hydrophilic and hydrophobic screens which are situated in parallel at a distance t from each other. We shall assume that the quantity t is selected from the condition $t/l < 1$, where l is the characteristic linear dimension of inclusions in the medium (droplets, bubbles), which exist (are generated) in the volume between the screens.

If we neglect the insignificant transport of inclusions along the surfaces, we can limit ourselves to the investigation of the dynamics of the free surface associated with individual inclusions during the process of their efflux through the corresponding screen which are initially suspended between the two solid surfaces.

It is expedient to apply variational methods based on the Hamilton principle and conditions of equilibrium for the action integral (J) in the case of true motions

$$\delta J = 0, \text{ where } J = \int_0^{\tau_1} (T - \Pi)\, d\tau.$$

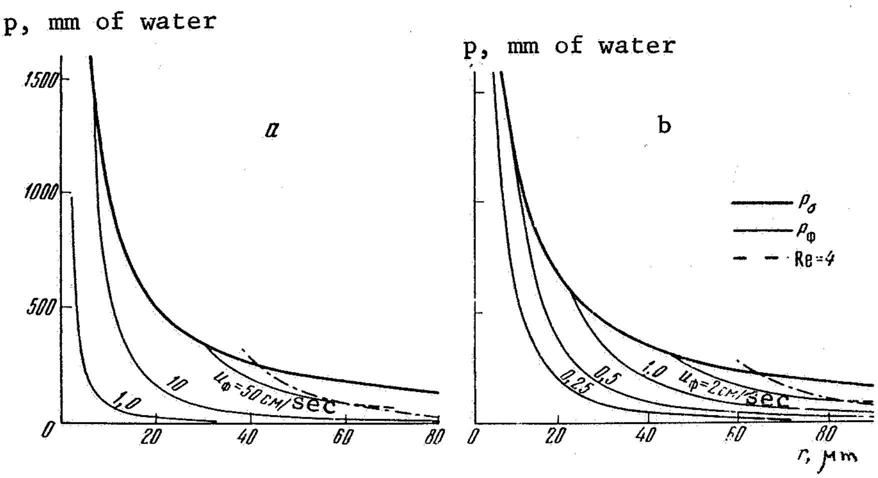

Figure 3. Variation in P_σ and P_Φ as a function of r for two cases: a-air-water-hydrophobic screen (θ=130°, s=0.5cm, W=0.4, σ=70 dyne/cm, $\mu=1.82\cdot 10^{-4}$ poises); b-air-water-hydrophilic screen (θ=20°, s=0.5cm, W=0.4, σ=70 dyne/cm, $\mu=10^{-2}$ poises).

Assuming that in this system the volumes ($V \sim t$) and velocities ($u \sim u_\Phi$) are small and that the surface forces (σ/t) prevail, we can neglect the integral of active forces $T=\frac{1}{2}\xi\int_V u^2 dV$ and reduce the problem to the establishment of a series of equilibrium surfaces which provide for the minimum potential energy of the system ($\delta\Pi=0$) during subsequent instants of time (here ξ is the density of the liquid).

The functional of the total potential energy (surface and volumetric) of the gas-liquid-hydrophobic-hydrophilic surface system (fig. 4) is given by:

$$\Pi = \sigma_{12}S_{12} + \sigma_{13}S_{13} + \sigma_{14}S_{14} + \sigma_{23}S_{23} + \sigma_{24}S_{24} + P_1V_1 + P_2V_2, \tag{4}$$

where σ_{ij} is the surface tension at the boundary of media i-j; S_{ij} is the contact area of phases i-j; P_1, V_1 are the total pressure and volume of the liquid at the given instant of time; P_2, V_2 are the total pressure and gas volume.

Euler's equation for this type of a functional (in the case of phase contact with a homogeneous surface) gives us (refs. 2 and 3)

$$2\sigma_{12}H-\lambda=0$$

(where H is the average curvature of the free surface, λ is the Lagrange multiplier) and the condition of transverseness $\sigma_{12}\cos\theta_1=\sigma_{23}-\sigma_{13}$ at the line of contact with the solid wall.

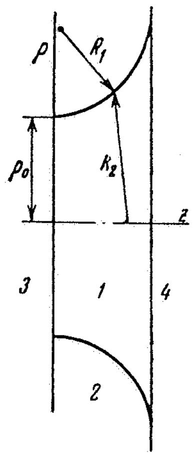

Figure 4. The initial position of a single inclusion. 1-liquid, 2-gas, 3-hydrophobic wall, 4-hydrophilic wall, R_1-meridional radius, R_2-equatorial radius of curvature.

By taking the variation of (4) we can see that the special feature associated with the presence of two solid surfaces with different surface energy leads to an additional condition for transverseness which is determined by the nature of the surface, and the unknown configurations of the flowing volume V_1 must satisfy the conditions: /717

$$\sigma_{12}\left(\frac{1}{R_1}+\frac{1}{R_2}\right)=P_1-P_2, \tag{5}$$

$$\cos\theta_1=\frac{\sigma_{23}-\sigma_{13}}{\sigma_{12}}, \tag{6}$$

$$\cos\theta_2=\frac{\sigma_{24}-\sigma_{14}}{\sigma_{12}}, \tag{7}$$

where R_1, R_2 are the radii of principal curvature and θ_1, θ_2 are the contact angles on the hydrophobic and hydrophilic surfaces.

It is obvious that in this case the unknown surfaces, which according to (5) have a constant average curvature, must also be surfaces of revolution whose axes of symmetry are normal with respect to the solid planes (fig.4) because these surfaces have a minimum value. Reducing equation (5) to a dimensionless form (multiplying it by t/σ_{12}) and expressing it in terms of cylindrical coordinates z, ρ (ref.4), we obtain a boundary value problem for determining the generatrixes of the family:

$$\rho\rho''-(1+\rho'^2)-\lambda\rho(1+\rho'^2)^{3/2}=0 \quad \left(\lambda=(P_1-P_2)\frac{t}{\sigma_{12}}\right) \tag{8}$$

with boundary conditions

$$\rho'(0)=\mathrm{tg}\,|90^\circ-\theta_1|, \tag{9}$$

$$\rho'(1)=\mathrm{tg}\,|90^\circ-\theta_2|, \tag{10}$$

and the parameter V_1, which may be conveniently introduced into the boundary conditions as an initial value ρ

$$\rho(0)=\rho_0. \tag{11}$$

The general solution of (8) is expressed in terms of normal elliptical Legendre integrals of the first and second kind

$$\rho+C_2=\frac{1}{h}F(\varphi,k)-\frac{1}{h'}E(\varphi,k)$$

$$[\varphi=\varphi(z);\ k=k(h',h);\ h,h'=h,h'(\rho_0,\theta_1,\theta_2)$$

which are the reduction constants and it becomes expedient to apply numerical methods. Certain difficulties in the numerical solution of this boundary value problem are produced by the initial arbitrary nature of the parameter λ.[1]

For this reason we first considered several limiting propositions which made it possible to determine the individual values of the function $\lambda(\rho_0)$ directly and the interpolation of these provided for a sufficient initial approximations of λ and good convergence of the iteration methods which were used. In particular equation (8) can be solved by quadrature (by assigning respectively the surface of a torus, a catenoid and a sphere: /718

- in the case of a large volume ($\rho_0 \gg 1$), when the equatorial curvature $1/R_2$ can be neglected ($R_2 \sim \rho_0$),

- in the case $R_1 = R_2$, when $\lambda = 1/R_1 + 1/R_2$ assumes a definite value: $\lambda = 0$ for curvatures of opposite sign $\lambda = 2/R_1$ for curvatures with the same sign.

A solution of the boundary value problem (8)-(11) was carried out by means of the M-20 electronic digital computer using iteration methods for values of parameter ρ_0 from 0 to 100. The method of obtaining the solution included the following:

- Integration of equation (8) by the Runge-Kutta method with initial conditions (9), (11) and initial approximation for λ;

- The automatic solution, by the iteration method, of the transcendental equation

$$\delta\rho'(\lambda) = \rho_k'(\lambda) - \rho_k' = 0, \tag{12}$$

where $\delta_\rho'(\lambda)$ is the discrepancy in the boundary conditions for z=1 in the next iteration step; $\rho_k'(\lambda)$ is the value of $\rho'(1)$ after integration with sequential approximation λ; ρ_k' is the boundary condition when z=1;

- The computation of the unknown curve with values for λ determined from (12).

The families of curves which have been obtained and which illustrate the dynamics of the free surface liquid and of the gas bubble are shown in figures 5 and 8 with superposed apexes. Figure 6 shows the relationships $\lambda(\rho_0)$ and $V(\rho_0)$, which express the dynamics of the dimensionless surface pressure as well as the correspondence between ρ_0 and the volume of the liquid.

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[1] Reference 5 presents the numerical integration of equation (8) carried out in a dimensionless form with respect to λ. However, solutions which are obtained in the case of this transformation (transformation of the type $\bar{z} = |\lambda| z, \bar{\rho} = |\lambda| \rho$) are not capable of representing the nature of changes in the surface when the volume varies because the transformation scale λ is generally a nonlinear function of the space factor (which is unknown in this case).

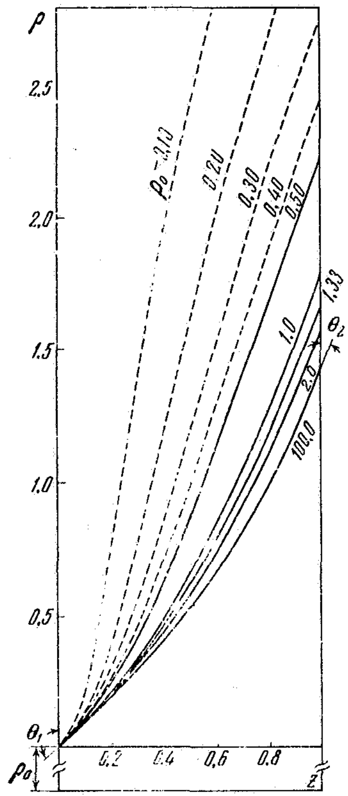

Figure 5. The dynamics of the liquid's free surface (θ_1=130°, θ_2=50°).

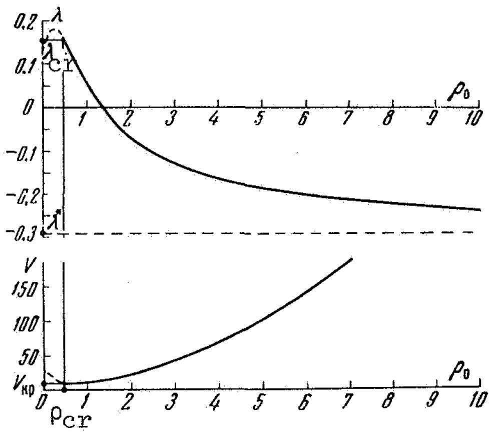

Figure 6. The dynamics of the liquid surface pressure.

By analyzing these curves we can see that:

- for large volumes (ρ_0>>1) the liquid surface is toroidal and approaches a catenoid as the volume is decreased; in this case the relative area of contact with the hydrophilic wall increases while contact with the hydrophobic wall decreases. The surface pressure is directed from the liquid to the gas and decreases monotonically in its absolute value from λ* (torus) to λ=0. /719

As the volume is further decreased the surface pressure increases at a very intense rate and is directed inside the liquid, thus providing for the natural drainage of the liquid:

- at a certain value $\rho_0=\rho_{cr}$ the volume

which has been described assumes its minimum value (see fig.6): when $\rho_0<\rho_{cr}$ the solutions

of (8) give configurations with an increase in the described volume (broken curves in figure 5), which is illustrated in figure 7. Since the liquid is incompressible, we can conclude that the volume V (ρ_{cr}) has a minimum value for which the stable position of the liquid in simultaneous contact with two surfaces is possible. As the volume decreases further the liquid breaks off from the hydrophobic surface. The form of the surface after the breakaway (ρ_0=0) represents a region of a sphere (figure 7).

The dynamics of the gas bubble is illustrated by the curves in figure 8. Analysis of these curves indicates that:

- the shape of the bubble corresponds to the predominance of the contact with hydrophobic surface; the relative area of the contact with the hydrophilic surface decreases sharply during the drainage process and when $\rho_0=\rho_{cr}$ the bubble breaks away from the latter;

- surface pressure is directed inside the bubble (λ>0) regardless of its dimensions and aids the drainage process (fig.9). /720

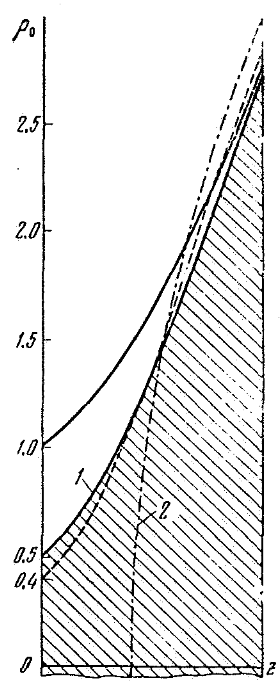

Figure 7. Form of the liquid before breakaway (1) from the hydrophobic surface and after breakaway (2).

The analysis which has been carried out makes it possible for us to conclude that in the system considered a mechanism of the volumetric separation of phases occurs; under these conditions, the surface forces provide for a total separation of inclusions from the unwetted (with respect to them) surface and for contact with the wetted surface.

4. In order to verify the conclusions which have been made, experimental investigations of the drainage process for water droplets and air bubbles which are initially suspended in the slit between the hydrophilic and hydrophobic elements, were carried out.

The height of the slit was selected from conditions of simulating weak gravity t=1.3-1.6mm (the Bond number had the respective values: $Bo=ng\xi t^2/\sigma=0.2-0.3$).

As an illustration, we can point out that the surface shapes which have been obtained (when modelling according to the Bo number) characterize the behavior of the liquid when, in particular, the slit has a height of 100 mm and gravity is reduced to $2\cdot10^{-4}$ g.[1]

The motion picture frames (figs. 10a and 11a) confirm completely the conclusions which have been made concerning the shape and dynamics of the free liquid surface and of the bubble in the considered system: /721

- in the initial instant of time ($\rho_0 >> 1$) the surface of the inclusion is toroidal,

- as the volume decreases the surface of the liquid approaches a catenoid,

- when $V=V(\rho_{cr})$ the liquid breaks away from the hydrophobic surface and the bubble breaks away from the hydrophilic surface and is completely removed from the considered volume.

For comparison purposes motion picture frames of the process (figs. 10b and 11b) are presented when the force of gravity is in the opposite direction (from the hydrophilic to the hydrophobic surface). In this case the separation of the phases is inhibited and we can see that the picture of the process remains practically unchanged and the laws specified above remain valid.

[1]According to Benedict (ref. 6), the critical values of the loading factor $n^*=\sigma/g\xi t^2$ (which, when exceeded, result in insignificant gravity) in both cases have the respective values n^* g=3g and $7.4\cdot10^{-4}$ g.

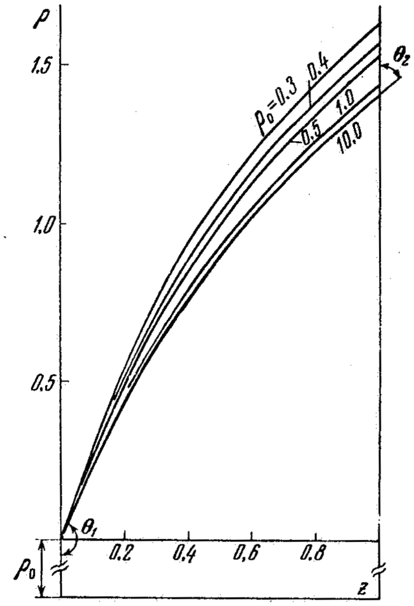

Figure 8. Dynamics of a bubble (θ_1=160°, θ_2=50°).

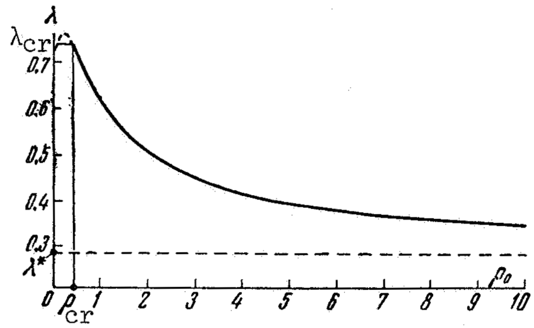

Figure 9. Dynamics of the bubble surface pressure.

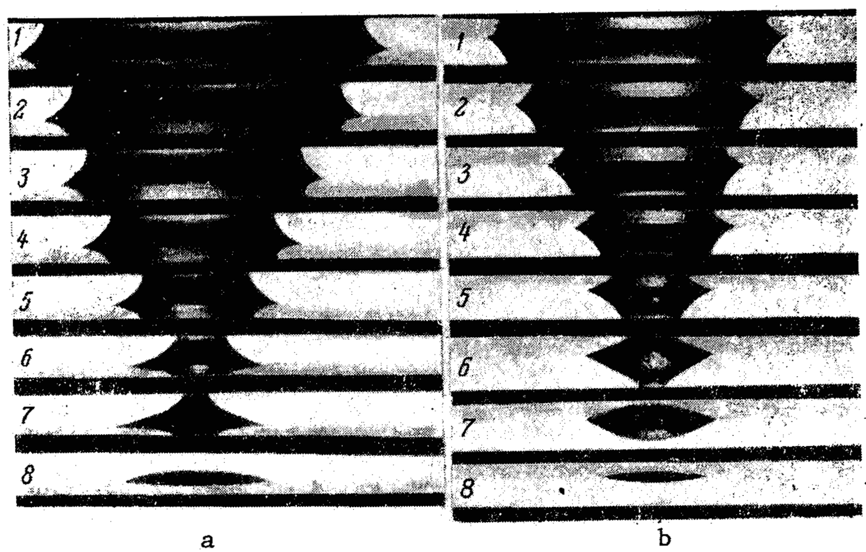

Figure 10. Dynamics of the liquid: a-g is directed straight from the hydrophobic to the hydrophilic surface (time in seconds): 1-0.0; 2-2.0; 3-4.0; 4-6.0; 5-8.0; 6-10.0; 7-10.2; 8-10.24; b-reverse direction of g: 1-0.0; 2-2.0; 3-4.0; 4-6.0; 5-8.0; 6-8.4; 7-8.44; 8-9.44.

The results which have been obtained also permit us to affirm that it is possible to model some elements to the hydrodynamics of weightlessness under laboratory conditions.

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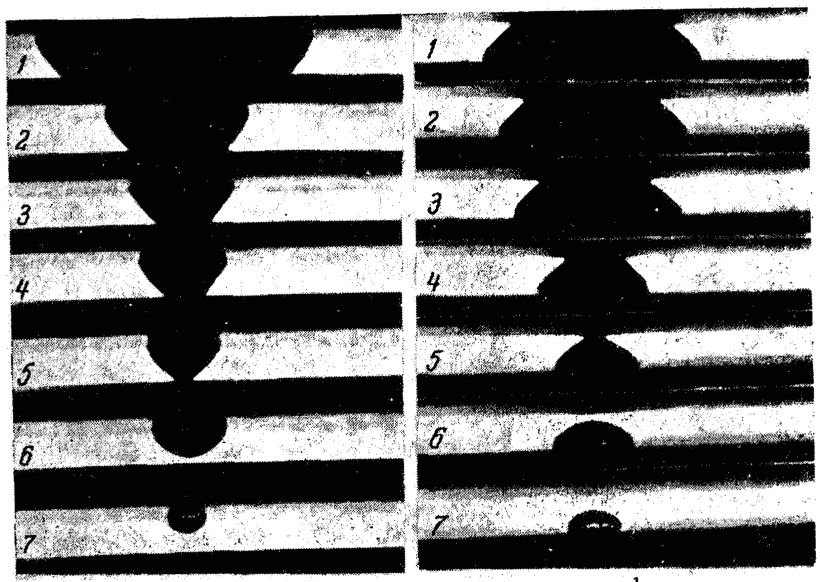

Figure 11. Dynamics of a bubble: a-forward direction (time in seconds): 1-0.0; 2-0.65; 3-1.15; 4-1.5; 5-1.8; 6-1.84; 7-2.5; b-reverse direction: 1-0.0; 2-0.65; 3-1.3; 4-3.3; 5-3.5; 6-3.54; 7-4.5.

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